COMBINED FINITE ELEMENT HUMAN THERMAL MODEL AND FINITE DIFFERENCE CLOTHING MODEL

Guozhi Fu and Byron W. Jones

Mechanical Engineering Department, *302* Durland Hall,
Kansas State University, Manhattan, KS 66506 U.S.A.

INTRODUCTION

Many situations where it is desired to model liuman tliermal responses involve complex environmental conditions and/or complex thermal response questions. Addressing these situations requires a simulation model that is equally detailed. Several detailed thermal-physiological models of the liuman body have been developed but generally these models have not included clothing or used very simplified mathematical descriptions of heat and moisture transport in tlie clothing. The models developed by Lotens [1] and by Jones and Ogawa [2] both have fully integrated transient clothing models. These models have proven to be useful and accurate for a variety of applications. However, both have limits as to tlie level of detail. In particular, neither can provide three-dimensional temperature inforination for the human body.

MATERIALS and METHODS

In the research reported here, a transient thee-dimension finite element thermal model for the liuman body was combined with a transient, quasi-two-dimensional model of clothing heat and moisture transfer. The liuman body model is based on tlie model developed previously by Smith [3]. The clothing model is based on the transient clothing model developed previously by Jones and Ogawa [2].

Smith's model consists of four parts: 1) tlie body tissue, *2)* tlie circulatory system, *3)* the respiratory system, and 4) the thermoregulatory control system. For tlie body tissue part, the body is divided into 15 parts, head, neck, torso, riglit and left upper arm, riglit and left lower arm, riglit and left liand, riglit and left thigh, riglit and left calf, and riglit and left foot. Each part is modeled as concentric cylinders and divided into smaller elements for tlie finite element solution of the governing equations. Altogether, there are 576 body tissue elements in Smith's model. Each tissue element is one of four types, bone, muscle, skin/fat, and internal organs, depending on its location. The circulatory system is modeled as a series of interconnected, branching vessels starting at tlie heart-lung element and returning to the heart-lung element. The vessels are modeled as one-dimensional fluid elements that lie at the edges of each tissue element and exchange heat at that location with tlie body tissue. A major artery and a major vein lie along tlie center of each body part except for tlie head. These branch out to smaller vessels of each type along the edges of the tissue elements. Only veins are present in the axial direction at the inner edge of the skin/fat layer and there are of course no vessels on tlie edges corresponding to the skin surface. The arteries and the veins only interconnect at the finest level of division. There are two return paths for the blood. One path is to return through the major veins that are at the center of each body part. The other is to return along the superficial veins under the skin/fat layer. The vessels are allowed to constrict and dilate according to signals received from tlie thermoregulatory control system in order to generate different flow patlis depending on the thermal state of the body. The circulatory system requires approximately 1500 elements in Smith's model. The respiratory system is modeled using dual interacting flow paths. Inspired air passes along one path from the mouth to tlie heart-lung node and tlie expired air passes though a separate path back to the mouth. The flow paths are modeled as one-dimensional fluid elements and lie along the edges of the appropriate elements. The respiratory air exchanges heat and moisture with the body tissue as it passes along these elements. At the heart-lung element, tlie air is saturated with moisture and is in thermal equilibrium with the tissue. The two passages communicate thermally to siinulate the regeneration effect that occurs in reality, For the thermal control system, Smith considered core and skin temperature as the doininant variables in determining thermoregulatory responses. By using published experimental data, empirical control equations were developed for determiningblood vessel radii, sweat rate, and shivering.

Smith's model was modified in two ways for the present research [4]. Heat exchange between the blood and body tissue via capillary beds was added using tlie equations given by Shitzer and Eberliart [5]. This heat transfer was included in the energy equations for the blood vessels and the tissue elements, but no attempt was made to model the fluid mechanics of the perfusion blood flow. Empirical control equations were added to determine tlie perfusion rate as a function of body thermal state. Also the skin and fat tissue layers were separated. This improved tlie accuracy of the siinulation for both cold and hot conditions primarily by allowing the superficial veins to be much closer to tlie skin surface.

The Jones and Ogawa clothing model is a quasi-two-dimensional representation of the transient, coupled heat and moisture transport. Locally, these processes are modeled as one-dimensional. However, the clothing can be divided over tlie surface of the body into as many independent parts as necessary to reflect local variations in body, clothing, and environmental conditioiis. Clothing is modeled geometrically as concentric layers around the body. Heat is transported across tlie intervening air layers by radiation and conduction and moisture is transported by diffusion. At the fabric, moisture may be adsorbed or condensed releasing the corresponding latent heat. These processes are modeled by keeping the fiber in equilibrium with the air in tlie surrounding micro climate, both with respect to moisture content and temperature. Both the thermal resistance and the evaporative resistance of the fabrics are include in the transport equations. Except for very thick fabrics, most of the thermal resistance occurs in the air layers and not the fabrics. However, all of the moisture-heat interactions occur in the fabrics. The moisture capacitance of the air **was** not included in the original version of this model but **was** added for the combined model.

The skin surface is the combination point for the two models. **A** moisture mass balance equation for the skin surface is solved to determine the water vapor pressure at the skin. This equation balances the sweat generated and the moisture diffused through the skin with the sweat evaporated from the skin surface. If the evaporation rate is insufficient to maintain a balance, sweat accumulates on the skin up to a maximum thickness of 35μm. Anytime there is accumulated moisture on the skin, the vapor pressure at the skin is equal to the saturation pressure. These calculations are made independently for each element of skin surface to account for local differences in sweat rate, clothing coverage, and/or environmental conditions.

Clothing is segmented by body part in the Jones and Ogawa model. The body parts are further segmented if the clothing coverage on that body **part** is not uniform. A database describing the clothing in this manner for over 40 clothing ensembles is a part of their model. In the combined model, it is necessary to describe the clothing coverage for each of the 176 skin elements. Thus each element must be assigned to one of the sub-segments in the clothing database. This assignment has not been automated and is rather tedious. Only selected ensembles have been converted in this manner to date.

RESULTS

The combined model was compared to experimental data collected in a previous study [6]. The actual heat and moisture dissipated by ten subjects to the environment under transient conditions were measured in a human calorimeter in this study. Data for ten different combinations of step changes in activity, temperature, and/or humidity were compared to the model for a 60 minute period following the step. In general the model predictions and the data agree within 10% for both heat and moisture dissipation throughout the period. This agreement is comparable to the estimated accuracy of the calorimeter measurements.

The combined model was then compared to a separate set of unpublished experimental skin temperature data. Twelve subjects moved from a steady state environment typical of room conditions to a hot (typically 45°C) or cold (typically -15°C) non-uniform environment. This hot or cold environment gradually changed back to a more nominal environment over a period of 30-45 minutes. Skin temperatures were measured on the chest, back, right and left forearm, and right and left thigh. The skin temperatures predicted throughout the transient period generally were within 1°C of the average for the subjects.

Computational requirements for the combined model are not trivial. It can run on Pentium based PC's but in excess of 32 megabytes of memory are required for efficient operation. On a HP 9000/750 work station, the ratio between computation time and simulation time is approximately one-to-one.

CONCLUSIONS

Computer simulation provides a powerful tool for assessing human thermal response and/or human thermal impact. No one model is likely to serve all needs and all applications. The simpler combined models [1,2] provide tools that are convenient and quick to use and are perfectly satisfactory for many applications. The combined human and clothing model presented here provides an additional tool that should prove useful where more detailed information is needed and justifies the increased computational requirements.

REF'ERENCES

1. Lotens, W. A., 1993, *Heat transfer from humans wearing clothing,* Elsevier Science Publishing Company, New York.
2. Jones, B. W. and Ogawa, Y., 1993, "Transient response of the human-clothing system, *Journal of Thermal Biology,* Vol. 18, No. 5/6.
3. Smith, C. E., 1991, **A** transient, three-dimensional model of the human thermal system, Ph.D. Dissertation, **Kansas** State University, USA.
4. Fu, G., 1995, A transient, **3-D** mathematical thermal model for the clothed human, P1i.D. Dissertation, Kansas State University, USA.
5. Shitzer, **A.** and Eberliart, R. C., 1985, Heat generation, storage, and transport processes, in Shitzer and Eberhart (eds.) *Heat transfer in medicine and biology, analysis and application,* Vol. **2,** Plenum Press, New York, 137-152.
6. B. W. Jones, Q. He, J. M. Sipes, and E. A. McCullough, 1994, "The Transient Nature of Thermal Loads Generated by People," *ASHRAE Transactions,* Vol. 100. Pt. 2.